5. CAPACITY VERSUS DEMAND

5.1 INTRODUCTION

A screening guideline which should be satisfied to evaluate the seismic adequacy of an item of equipment identified in the Seismic Equipment List (SEL), as described in Chapter 4, is to confirm that the seismic capacity of the equipment is greater than or equal to the seismic demand imposed on it. This chapter addresses the determination of the seismic demand and capacity for the equipment as well as the comparison of the demand to the capacity. Note that a comparison of seismic capacity to seismic demand is also made in Chapter 6 for the equipment anchorage, in Chapter 9, Section 10.4.1, Section 10.4.3, and Section 10.5.1 for the equipment class evaluations using screening procedures, and in Chapter 11 for relays mounted in the equipment.

This chapter first presents the general description and techniques for computing the seismic demand and capacity, followed by the comparison of the demand to the capacity. In Section 5.2, the seismic demand is defined by the Seismic Demand Spectrum (SDS). The SDS is based on the Design Basis Earthquake (DBE) as defined for DOE facilities. The input motion for the equipment is determined by computing an in-structure response spectrum based on the DBE and the frequency response of the structure in which the equipment is mounted. Scaling factors are applied to the in-structure response spectrum to compute the SDS. In Section 5.3, the seismic capacity is represented by the Reference Spectrum, Generic Equipment Ruggedness Spectrum (GERS), or qualification test spectrum. Note that the Reference Spectrum and GERS can be used for representing seismic capacity of equipment only if the equipment meets the intent of the caveats for its equipment class as described in Chapter 8. Finally, in Section 5.4 the SDS is compared to the appropriate capacity spectrum.

The DOE Seismic Evaluation Procedure is intended primarily for systems and components identified as Performance Category (PC)-2 or higher. As discussed in DOE Orders and standards, the performance goal description for PC-1 is to maintain occupant safety during and/or immediately following an earthquake, while PC-2 and higher categories add goals such as continued operation with minimum interruption. Within the DOE graded approach, the primary concern for PC-1 structures is to prevent major structural damage or collapse that would endanger personnel. This concern is consistent with the goal of the model building codes, such as the Uniform Building Code (UBC) (Ref. 69), for general facilities to maintain life safety during earthquakes. The provisions of the UBC or similar building code should be followed for PC-1 systems and components since continued operation is not a requirement. For PC-2 and higher systems and components, the provisions of the DOE Seismic Evaluation Procedure satisfy the qualitative description of the performance goals for those categories and can be used to evaluate their capacity to at least have continued operation with minimum interruption during and/or immediately following an earthquake.

5.2 SEISMIC DEMAND

5.2.1 Design Basis Earthquake

For DOE facilities, the Design Basis Earthquake (DBE) is a specification of the mean seismic ground motion at the facility site for the earthquake-resistant design or evaluation of the structures, systems, and components at that site. The DBE is defined by ground motion parameters determined from mean seismic hazard curves and a design response spectrum shape. These hazard curves relate hazard exceedance probabilities to response quantities, such as peak ground acceleration. The methodologies for determining the seismic environment are described in DOE-STD-1022 (Ref. 70) and DOE-STD-1023 (Ref. 71). While DOE-STD-1022 provides procedures for site characterization, DOE-STD-1023 provides procedures for the development of hazard curves and spectra, such as the DBE, using parameters determined from the site characterization.

Many DOE sites have determined their site-specific DBE and have documented information about their DBE in Safety Analysis Reports (SARs) and reports in the hazards control or plant engineering departments of the DOE site.

As discussed in DOE-STD-1020 (Ref. 6), the preferable shape for the median deterministic DBE response spectrum should be site-specific and consistent with earthquake hazard parameters such as magnitudes, distances, and soil profiles. If a site-specific response spectrum shape is unavailable, a median standardized spectral shape may be used as long as the shape is consistent with or conservative for the site conditions. A recommended standardized spectral shape is shown in Figure 5.2-1, which is the shape defined in NUREG/CR-0098 (Ref. 72). The control points for the spectral shape in Figure 5.2-1 are provided in Table 5.2-1.

Table 5.2-1 Control Points for NUREG/CR-0098 Spectral Shape

Frequency (Hertz)	Spectral Acceleration (g)
0.1	$0.395\ d_{max} / g$
$v_{max} / (2 \pi d_{max})$	$v^2_{max} / (g\ d_{max})$
$(g\ a_{max}) / (2 \pi v_{max})$	a_{max}
8.0	a_{max}
33.0	a_g
100.0	a_g

where (for competent soil, $V_s < 3{,}500$ ft/sec, and for 50% spectra):

PGA - peak ground acceleration

β - percent damping

g = acceleration due to gravity (in/sec^2)

a_g = PGA (g)

v_g = $48\ a_g$ (in/sec)

d_g = $36\ a_g$ (in)

a_{max} = $a_g\ (3.21 - (0.68 \ln \beta))$

v_{max} = $v_g\ (2.31 - (0.41 \ln \beta))$

d_{max} = $d_g\ (1.82 - (0.27 \ln \beta))$

DOE-STD-1020 also discusses techniques for addressing the effective peak acceleration as compared to the predicted instrumental peak ground acceleration reported in some probabilistic seismic hazard assessments for sites at short epicentral distances. Typically, the effective peak acceleration is lower than the peak ground acceleration. While it is appropriate in seismic evaluations to remove sources of excessive conservatism, use of the effective peak acceleration for the evaluation of the functionality of active systems and components may not be conservative and should be peer reviewed on a site-specific basis. The effective peak acceleration may not be conservative because many types of active systems and components are relatively stiff and may no longer operate if the seismic demand requires inelastic response to the peak ground acceleration.

In order to demonstrate that DOE facilities are capable of resisting a specified level of seismic demand, it must be demonstrated that there is a sufficiently low probability of damage or failure of those facilities consistent with established performance goals as defined in DOE Orders and DOE-STD-1020. As discussed in Sections 1.2 and 4.1, the annual exceedance probability for a facility is determined by its performance category and the equipment in the SEL are classified into a particular performance category in accordance with DOE-STD-1021 (Ref. 7). Associated with each performance category is a different performance goal and an accompanying hazard exceedance probability which specifies the level of the DBE for each category.

DOE-STD-1020 permits some relief in the criteria for the seismic evaluation of systems and components in existing facilities. For existing facilities, the seismic evaluations may use a natural phenomena hazard exceedance probability that is twice the value specified for new facilities. This relief corresponds to a slight reduction (approximately 10-20%) in the seismic loads for the DBE. The basis of this slight reduction is contained in Reference 73. Use of the relief for specific existing facilities should follow the provisions in DOE-STD-1020.

The DBE is established at a higher annual frequency of occurrence than the acceptable annual probability of failure of the structures, systems, or components, so scale factors and experience data factors are required to achieve the appropriate risk reduction. These scale factors are similar to safety factors or the inherent conservatism in the acceptance criteria of structural design codes. The basis for the scale factors is provided in References 24 and 73 and the scale factors are shown in Table 5.2-2.

Table 5.2-2 Scale Factors

Performance Category[1]	Scale Factor (SF)
2	0.67
3	1.00
4	1.25

In the design of new equipment, rules are specified such that a known margin exists between the design value and the ultimate failure level. This margin has been considered in developing the provisions of DOE-STD-1020 as discussed in References 6, 24, and 73. A similar margin is required for the use of capacity obtained from experience data. Section 5.3 discusses the different types of capacity representation. The margin between the design and ultimate failure values are contained in the experience data factor, F_{ED}, defined in Reference 24 and shown in Table 5.2-3.

Table 5.2-3 Experience Data Factors

Capacity Representation[2]	F_{ED}
Reference Spectrum	1.0 SF
GERS	1.4 SF
Relay GERS	1.8 SF
Qualification Test	1.4 SF

[1] The Performance Category for each item of equipment in the SEL is determined using the provisions in Chapter 4 and DOE-STD-1021 (Ref. 7).

[2] Definitions for the different capacity representations are provided in Sections 2.1.3.1 and 5.3.

5.2.2 In-Structure Response Spectrum[3]

For buildings, the DBE defines the seismic demand at the foundation of the structure. For equipment, the demand is defined in terms of the input motion applied at the appropriate attachment point(s) of the equipment. This demand or input motion is generally represented by an in-structure response spectrum (IRS). The IRS will differ significantly from the DBE spectrum because it is essentially filtered and / or amplified through the building. To use the provisions of the DOE Seismic Evaluation Procedure, the demand at the attachment point(s) of the equipment must consider the effects of structural filtering and / or amplification. Methods for determining the IRS with dynamic analyses are described in DOE-STD-1020 (Ref. 6) and ASCE 4 (Ref. 74). As discussed in ASCE 4, the IRS must account for uncertainties by spectral broadening or peak shifting. Additional guidance on computing IRS is provided in Sections 2.3 and C.4 of DOE-STD-1020. In DOE-STD-1020, dynamic analyses which may use IRS are only specified for PC-3 and PC-4 systems and components. In order to use the methodology in the DOE Seismic Evaluation Procedure, IRS should be developed as well for PC-2 systems and components in the SEL. Guidance for determining in-structure spectra for PC-2 systems and components is provided in the model building codes such as the UBC (Ref. 69) and the National Earthquake Hazards Reduction Program (NEHRP) Provisions (Ref. 75).

Realistic, median-centered in-structure response spectra are defined as response spectra which are based on realistic damping levels for the structure (including the effects of embedment and wave-scattering) and on structural dynamic analysis using realistic, best estimate modeling parameters and calculational methods such that no intentional conservatism enters into the process. These in-structure response spectra should be based on a ground response spectrum defined by the DBE as determined in DOE-STD-1023. For existing facilities with an approved Safety Analysis Report (SAR), the in-structure response spectra included in the SAR may be used as appropriate. Examples of realistic damping values are given in DOE-STD-1020 and EPRI Report NP-6041 (Ref. 18). The effects of embedment, wave scattering, and other soil-structure interaction (SSI) effects can be accounted for by using the methods in ASCE 4 by using frequency shifting rather than peak broadening. A spectral reduction factor can be used for considering the effects of horizontal spatial variation.

DOE-STD-1020 recommends the procedures in ASCE 4 for generating in-structure response spectra. The experience data factors, F_{ED}, listed in Table 5.2-3 are appropriate when the in-structure response spectra are generated in accordance with DOE-STD-1020. In some cases, in-structure response spectra may be developed with varying conservatism which is different than that defined in DOE-STD-1020. Reference 24 outlines methods to account for variation in the determination of in-structure response spectra with different levels of conservatism. The Seismic Safety Margins Research Program (Ref. 57 and 58) has demonstrated the large conservatism which exists in traditionally-computed, conservative design in-structure response spectra versus realistic, median-centered in-structure response spectra. The specific assumptions made in generating in-structure response curves should be reviewed by SCEs using the guidance provided in Appendix A of Reference 19.

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[3] Based on Section 4.2.4 of SQUG GIP (Ref. 1)

5.2.3 Seismic Demand Spectrum

To evaluate the seismic demand at the attachment point(s) of equipment, an in-structure response spectrum (IRS) is scaled by F_{ED} to determine the Seismic Demand Spectrum (SDS) according to the following equation:

$$SDS = F_{ED} \times IRS$$

where:

SDS - Seismic Demand Spectrum or Scaled In-Structure Response Spectrum. For relays, the SDS is modified to account for in-cabinet amplification. Chapter 11 provides two methods for modifying the SDS for relays mounted in cabinets.

F_{ED} - Experience Data Factor. It depends on the performance category and capacity representation of the equipment and is defined in Tables 5.2-2 and 5.2-3.

IRS - In-Structure Response Spectrum. It is determined for the appropriate attachment point(s) of the equipment and is a function of the DBE for the facility and the frequency content of the structure supporting the equipment.

Additional information on techniques for computing the seismic demand spectrum are provided in Step 1 of Section 6.4.2. In this section, an approximate technique for scaling seismic demand spectra, which are defined for different damping values, is discussed.

5.2.4 Total Demand

The total demand (D_{TI}) is a combination of seismic loads (D_{SI}) and concurrent non-seismic loads (D_{NS}).

$$D_{TI} = D_{SI} + D_{NS}$$

where:

D_{TI} - Total Demand

D_{SI} - Seismic Loads. According to DOE-STD-1020 (Ref. 6), the dynamic analyses used to compute the seismic loads for PC-3 and PC-4 systems and components must consider all three orthogonal components of earthquake ground motion (two horizontal and one vertical). In order to use the methodology in the DOE Seismic Evaluation Procedure, all three orthogonal components of earthquake ground motion should be considered for PC-2, PC-3, and PC-4 systems and components. The earthquake ground motion is described by the SDS defined in Section 5.2.3. For near-field sites, the vertical component of the DBE may exceed the horizontal components. Responses from the various directional components should be combined with acceptable combinations techniques, such as the Square-Root-Sum-of-the-Squares (SRSS) and the 100-40-40-Rule, in accordance with ASCE 4 (Ref. 74).

D_{NS} - Non-Seismic Operational Loads

When comparing D_{TI} to seismic capacity based on earthquake experience data as defined in Section 5.3.1 or generic seismic testing data as defined in Section 5.3.2, the effects of all three orthogonal components of the earthquake ground motion and the effects of non-seismic operational loads are typically not explicitly considered for equipment adequacy assessment as described below:

(a) According to Section 4.2.3 of the SQUG GIP (Ref. 1), the vertical component of the ground response spectrum is not explicitly considered for equipment adequacy assessment. In general, it is considered that equipment is more sensitive to horizontal motion than vertical motion. Evaluation of the effects of the vertical component is implicit in the horizontal motion assessment since the earthquake-experience facilities typically experienced relatively higher vertical motion than that explicitly considered. When using GERS, the generic seismic testing included effects of vertical motion which was consistent with that explicitly considered.

(b) Equipment in the earthquake-experience database was subjected to non-seismic operating loads concurrent with the seismic loads. In many cases, the non-seismic loads were implicitly included along with the horizontal seismic loads and in defining the caveats for the Reference Spectrum. Note that there may be facility-specific equipment that is subjected to operating loads which were not implicitly included in the experience database. For equipment subjected to both operating and seismic loads, the database may need to be reviewed to determine if the operating loads were implicitly considered. If the operating loads were not implicitly considered, then their effects should be considered concurrently with the seismic loads.

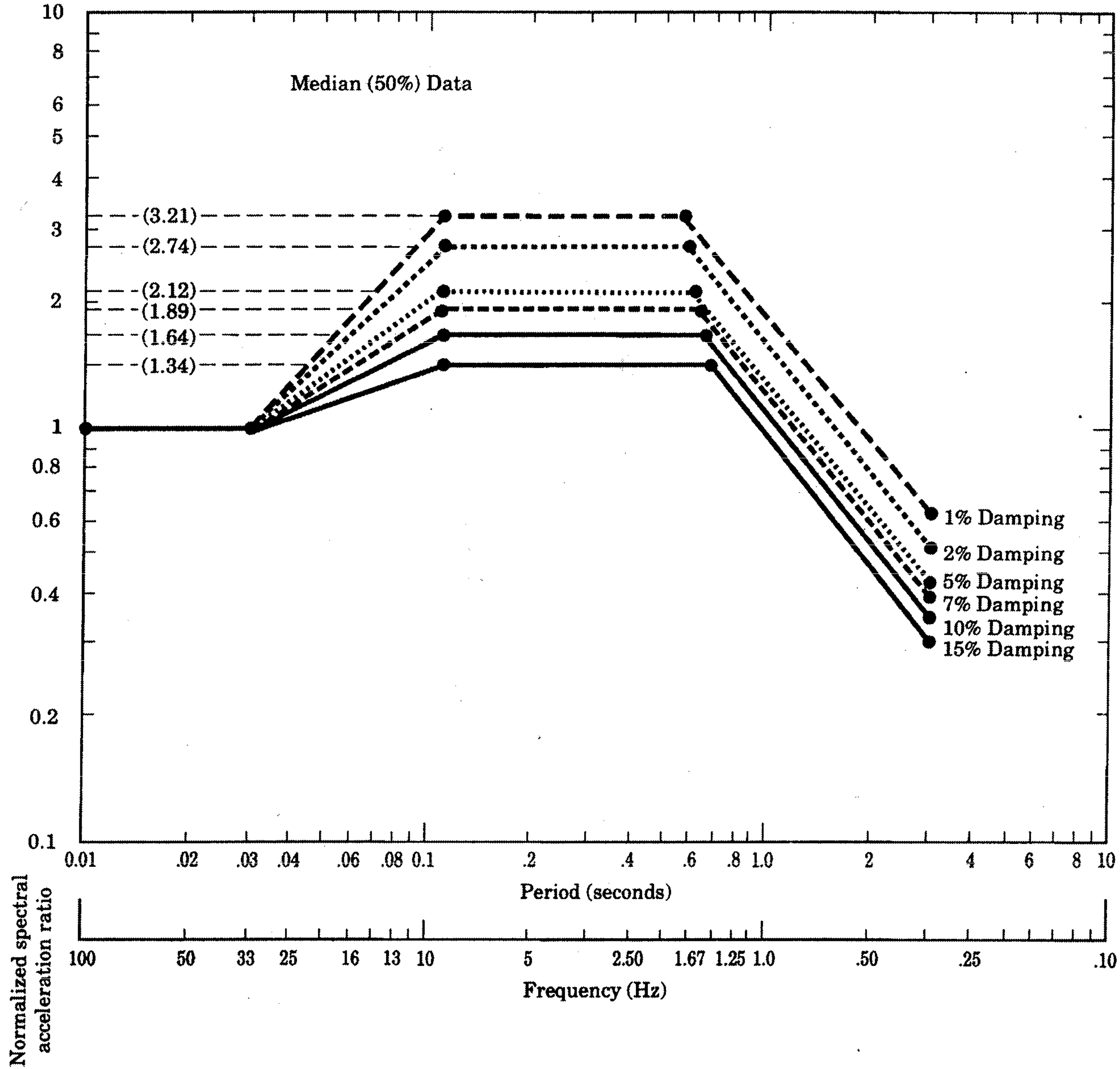

Figure 5.2-1 Median Standardized Spectral Shape Defined in NUREG/CR-0098, the Newmark and Hall 50% Exceedance Horizontal Spectra for Soil (References 72 and 76)

5.3 EQUIPMENT CAPACITY

5.3.1 Seismic Capacity Based on Earthquake Experience Data[4]

Earthquake experience data was obtained by surveying and cataloging the effects of strong ground motion earthquakes on various classes of equipment mounted in conventional power plants and other industrial facilities. The results of this effort are summarized in Reference 35. Based on this work, a Reference Spectrum was developed which represents the seismic capacity of equipment in the earthquake experience equipment class. A detailed description of the derivation and use of this Reference Spectrum is contained in Reference 19 and this reference should be reviewed by the SCEs before using the Reference Spectrum. The Reference Spectrum and the four spectra from which it is derived are shown in Figure 5.3-1. Figure 5.3-2 shows the Reference Spectrum and its defining response levels and frequencies.

The Reference Spectrum can be used to represent the seismic capacity of equipment in a DOE facility when this equipment is determined to have characteristics similar to the earthquake experience equipment class and meets the intent of the caveats for that class of equipment as defined in Chapter 8. Use of the Reference Spectrum for comparison with the Seismic Demand Spectrum (SDS) is described in Section 5.4.

5.3.2 Seismic Capacity Based on Generic Seismic Testing Data[5]

A large amount of data was collected from seismic qualification testing of nuclear power plant equipment. This data was used to establish a generic ruggedness level for various equipment classes in the form of Generic Equipment Ruggedness Spectra (GERS). The development of the GERS and the limitations on their use (caveats) are documented in Reference 40. Copies of the non-relay GERS along with a summary of the caveats to be used with them are included in Chapter 8. A copy of a relay GERS is included in Chapter 11. SCEs should review Reference 40 to understand the basis for the GERS.

GERS can be used to represent the seismic capacity of an item of equipment in a DOE facility when this equipment is determined to have characteristics which are similar to the generic testing equipment class and meets the intent of the caveats for that class of equipment as defined in Chapter 8. Use of the GERS for comparison with the Seismic Demand Spectrum (SDS) is described in Section 5.4.

5.3.3 Equipment-Specific Seismic Qualification

Equipment-specific seismic qualification techniques, as used in newer DOE facilities, may be used instead of the methods given in Section 5.3.1 and 5.3.2. With this technique, shake-table tests should be performed in accordance with IEEE-344-75 Standards (Ref. 12) or more current standards.

Equipment-specific seismic qualification can be useful for equipment classes discussed in Chapter 10. Some of these equipment classes do not have the Reference Spectrum or GERS to define their capacity. With seismic qualification techniques, a test spectrum can be generated for these classes of equipment and this spectrum must be scaled with the F_{ED} for Qualification Test in Table 5.2-3.

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[4] Based on Section 4.2.1 of SQUG GIP (Ref. 1)

[5] Based on Section 4.2.2 of SQUG GIP (Ref. 1)

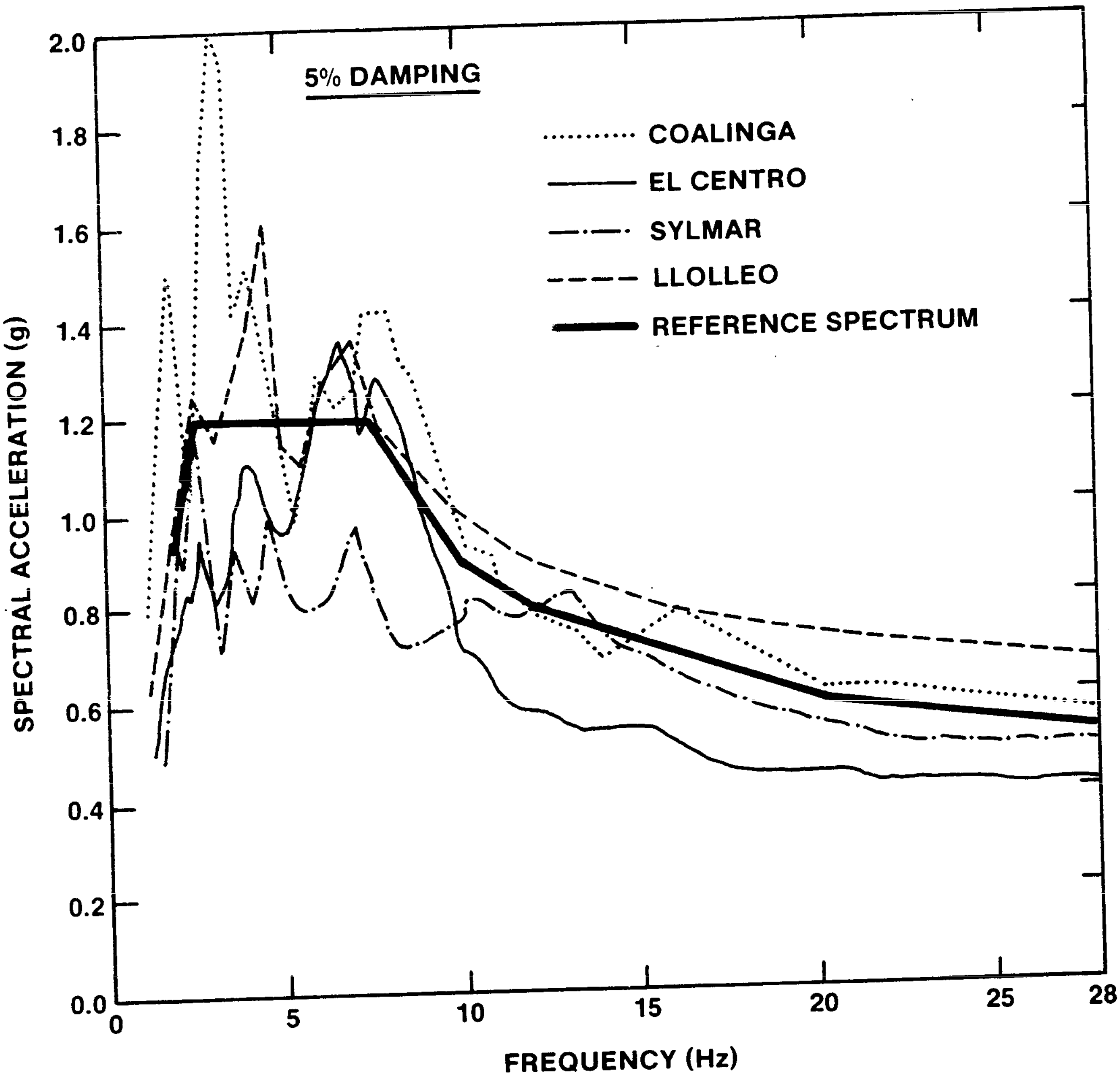
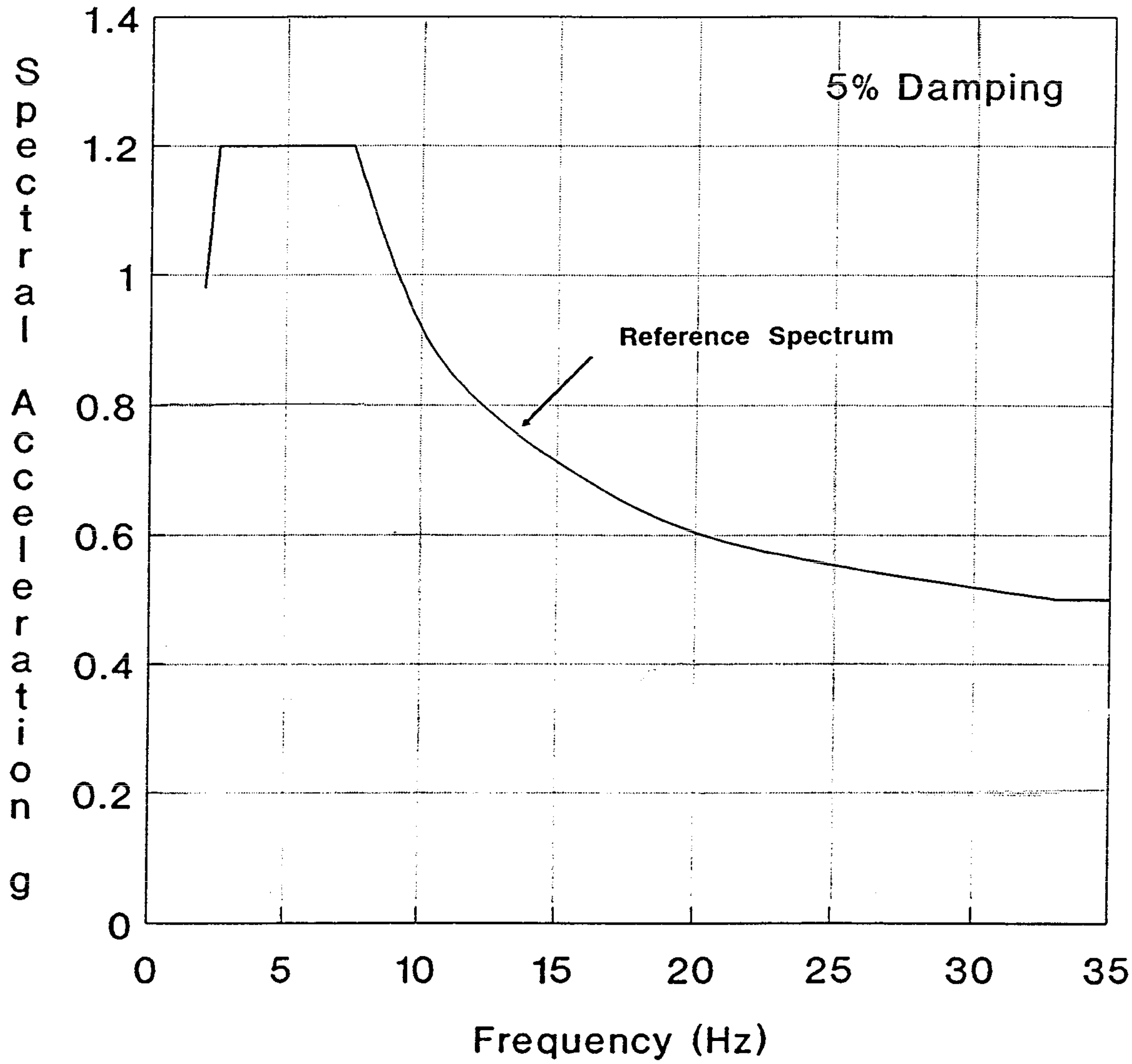


Figure 5.3-1 Horizontal Response Spectra Representing the Earthquake Experience Database (Reference 19)



Frequency (Hz)	2.0	2.5	7.5	8.0	10	12	16	20	28	33
Spectral Acceleration (g)	.98	1.2	1.2	1.13	.90	.80	.68	.59	.53	.50

Figure 5.3-2 Seismic Capacity Represented by Reference Spectrum Based on Earthquake Experience Database (Figure 4-2 of SQUG GIP, Reference 1)

5.4 EXPERIENCE-BASED CAPACITY COMPARED TO SEISMIC DEMAND

This section addresses the comparison of experience-based seismic capacity to seismic demand for the equipment. The seismic capacity of equipment can be represented by a Reference Spectrum based on earthquake experience data, a Generic Ruggedness Spectrum (GERS) based on generic seismic test data, or a test spectrum from equipment-specific seismic qualification as respectively described in Sections 5.3.1, 5.3.2, and 5.3.3. Note that the first two methods of representing seismic capacity of equipment can only be used if the equipment meets the intent of the caveats for its equipment class as described in Chapter 8. The seismic capacity of an item of equipment is compared to its seismic demand which is defined in terms of an in-structure response spectrum (IRS). As discussed in Section 5.2, the IRS is scaled with the applicable scale factors to determine the Seismic Demand Spectrum (SDS).

5.4.1 Comparison of Equipment Seismic Capacity to Seismic Demand[6]

An in-structure response spectrum can be used for comparison to Reference Spectrum, GERS, or test spectrum for equipment which is mounted at any elevation in the facility and/or for equipment with any natural frequency. The Reference Spectrum, GERS, or test spectrum are used to represent the capacity of the equipment. The SDS associated with the DBE for a DOE facility can be used to represent the seismic demand applied to the facility equipment. One of the following comparisons of capacity and demand, as illustrated in Figure 5.4-1, is made:

- Reference Spectrum envelops the Seismic Demand Spectrum (SDS)

  Reference Spectrum (Section 5.3.1) $\geq$ SDS

- GERS envelops the Seismic Demand Spectrum (SDS)

  GERS (Section 5.3.2) $\geq$ SDS

- Test spectrum envelops the Seismic Demand Spectrum (SDS)

  Seismic Qualification Tests (Section 5.3.3) $\geq$ SDS

- Relay GERS envelops the In-cabinet Demand Spectrum (IDS). Section 11.3 discusses techniques for calculating the IDS using the Seismic Demand Spectrum (SDS).

  Relay GERS (Section 11.2) $\geq$ IDS

For these comparisons, the largest horizontal component of the 5% damped in-structure response spectra is used for the location in the facility where the item of equipment is mounted. An approximate technique for scaling in-structure response spectra by their damping ratios is provided in Section 6.4. The in-structure response spectrum used for the seismic demand should be representative of the elevation in the structure where the equipment is anchored and receives its seismic input. This elevation should be determined by the SCEs during the facility walkdown. If one of the comparisons shown above is not satisfied, then the equipment being evaluated is an outlier. Methods for resolving outliers are provided in Chapter 12.

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[6] Based on Section 4.2.4 of SQUG GIP (Ref. 1)

5.4.2 Enveloping of Seismic Demand Spectrum[7]

To evaluate seismic adequacy, in general, the seismic capacity spectrum should envelop the SDS over the entire frequency range of interest (typically 1 to 33 Hz). There are two special exceptions to this general rule:

- The seismic capacity spectrum needs only to envelop the SDS for frequencies at and above the conservatively estimated lowest natural frequency of the item of equipment being evaluated.

  Caution should be exercised when using this exception because an equipment assembly (e.g., electrical cabinet lineup) may consist of many subassemblies, each manifesting its fundamental mode of vibration at different frequencies. The lowest natural frequency of each subassembly should be determined with high confidence using the guidance provided below in Section 5.4.3. It is noted that unless the equipment is tested with a high-level vibratory input, the fundamental frequency can be difficult to estimate, especially for complex structural equipment.

- Narrow peaks in the SDS may exceed the seismic capacity response spectrum if the average ratio of the SDS to the capacity spectrum does not exceed unity when computed over a frequency range of 10% of the peak frequency (e.g., 0.8 Hz range at 8 Hz). Note that it is permissible to use unbroadened SDS for this comparison, however when doing so, uncertainty in the natural frequency of the building structure should be addressed by shifting the frequency of the SDS at these peaks. An acceptable method of peak shifting is described in ASCE 4 (Ref. 74). A reference or basis for establishing the degree of uncertainty in the natural frequency of the building structure should be included in the facility-specific seismic evaluation records.

If either of these exceptions are used, the Screening Evaluation Work Sheets (SEWS) should be marked to indicate the exception that has been invoked.

5.4.3 Lowest Natural Frequency[8]

When it is necessary to determine the lowest natural frequency of an item of equipment, the SCEs may, in most cases, estimate a lower bound for this frequency based on their experience, judgment, and available data. Methods for frequency estimation are provided in Reference 77. The lowest natural frequency of concern is that of the lowest natural mode of vibration that could adversely affect the safety function of the equipment. The modes of vibration which should be considered are:

- The overall structural modes of the equipment itself and

- The modes for internal structures (e.g., flexural mode for door panels) which support components needed to accomplish the safety function of the equipment.

- The modes of devices which are needed to accomplish the safety function of the equipment. A value of 5 Hertz is recommended and higher values should be appropriately justified.

In addition, the SCEs should also be alert and note any items of concern within the "box" which could be seismically vulnerable. This would include components mounted in the "box" which have known low natural frequencies, seismic vulnerabilities, or improper mounting (e.g., loose or

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[7] Based on Section 4.2 of SQUG GIP (Ref. 1)

[8] Based on Section 4.2 of SQUG GIP (Ref. 1)

missing bolts). If these types of situations are found during the seismic review, their presence may constitute a third type of vibrational mode and their influence should be included in the estimate of the lowest natural frequency and the assessment of the seismic adequacy of the equipment.

5.4.4 Guidance for Evaluating In-Line Equipment[9]

The amplified response of in-line equipment which is supported by piping (e.g., valves, valve operators, and sensors) is handled differently when using the Reference Spectrum or the GERS as the seismic capacity of the equipment. When using the Reference Spectrum, it is not necessary to account for amplification of the piping system between the anchor point of the piping system (i.e., the floor or wall of the building) and the point on the piping system where the item of equipment is attached. This is because the effect of amplified response in piping systems is accounted for in the earthquake experience data base.

When using GERS as the seismic capacity of equipment, piping system amplifications should be accounted for when establishing the seismic demand on the in-line item of equipment. The amplification factor can be obtained from a dynamic piping analysis if one is available. As an alternative, the amplification factor may be estimated using judgment with peer review.

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[9] Based on Section 4.2.4 of SQUG GIP (Ref. 1)

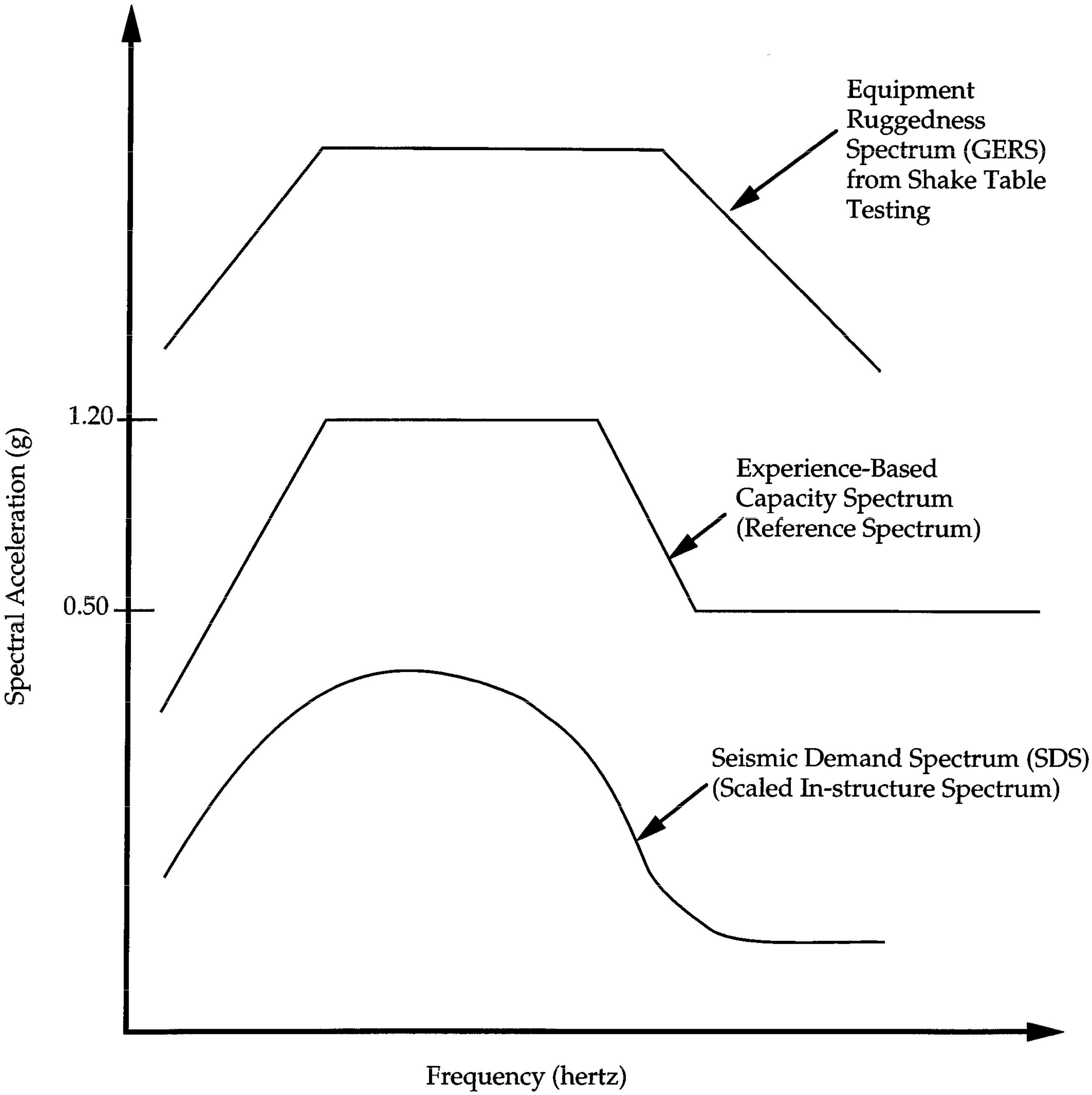

Figure 5.4-1 Comparison of Seismic Capacity Spectrum to Seismic Demand Spectrum